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IPM for fresh-market lettuce production in the desert southwest: the produce paradox

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Abstract

In the 'Integrated Control Concept', Stern *et al*. emphasized that, although insecticides are necessary for agricultural production, they should only be used as a last resort and as a complement to biological control. They argued that selective insecticide use should only be attempted after it has been determined that insect control with naturally occurring biotic agents is not capable of preventing economic damage. However, they concluded their seminal paper by emphasizing that integrated control will not work where natural enemies are inadequate or where economic thresholds are too low to rely on biological control. Thus, it is no surprise that insect control in high-value, fresh-market lettuce crops grown in the desert southwest have relied almost exclusively on insecticides to control a complex of mobile, polyphagous pests. Because lettuce and leafy greens are short-season annual crops with little or no tolerance for insect damage or contamination, biological control is generally considered unacceptable. High expectations from consumers for aesthetically appealing produce free of pesticide residues further forces vegetable growers to use chemical control tactics that are not only effective but safe. Consequently, scientists have been developing integrated pest management (IPM) programs for lettuce that are aimed at reducing the economic, occupational and dietary risks associated with chemical controls of the past. Most of these programs have drawn upon the integrated control concept and promote the importance of understanding the agroecosystem, and the need to sample for pest status and use action thresholds for cost-effective insect control. More recently, pest management programs have implemented newly developed, reduced-risk chemistries that are selectively efficacious against key pests. This paper discusses the influence that the integrated control concept, relative to zero-tolerance market standards and other constraints, has had on the adoption of pest management in desert lettuce crops.

Keywords: integrated control; selective insecticides; consumer perceptions; sampling

1 INTRODUCTION

In originating their concept of integrated control, Stern *et al*.[1] clearly recognized the economic realities and environmental consequences of insecticide use in western agriculture. Their motivation for developing the integrated control concept (ICC) was prompted by the serious problems (i.e. resistance, secondary pest outbreaks, pest resurgence and excess residues on food) that resulted following the 'widespread and indiscriminate' use of the newly introduced organochlorine insecticides. They logically argued that, although chemical control of insect pests is often necessary, it should only be utilized following the determination that naturally occurring biotic agents are not able to prevent economic damage. Stern and his colleagues envisioned cropping systems where selective insecticide use, dictated by economic thresholds and population sampling, would be employed as a last resort to complement the actions of biological control. However, when discussing the future of integrated control in the concluding section of their seminal paper, Stern *et al*.[1] emphasized that integrated control is not a 'panacea', and would not work in crops where 'biotic mortality agents are inadequate or if low economic thresholds preclude utilizing biological control'.

Taken literally, their conclusion suggested that integrated control would not work in fresh-market lettuce and leafy greens being grown in the southwestern United States today, where blemish-free produce is expected and insect contamination is not acceptable. And, for the most part, they were correct. Nonetheless, it is apparent 50 years later that many of the fundamental principles found in the ICC have had a significant influence on how insect populations are presently managed on desert lettuce crops, albeit with scant attention paid to the role of natural enemies or other biotic mortality agents. The focus of this paper is to provide an overview of why growers in the southwestern United States rely almost exclusively on chemical control for insect management in lettuce and leafy greens, why they have failed to adopt biointensive pest management and yet how, through the use of novel, reduced-risk insecticides and IPM-conscious approaches, they have been able to accommodate strict market and regulatory demands for high-quality produce that is safe and aesthetically appealing.

2 WHY INTEGRATION OF BIOLOGICAL AND CHEMICAL CONTROL IS NOT FEASIBLE IN DESERT LETTUCE

In many vegetable production systems, it is not possible to completely rely on biological control to manage important pests,

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and judicious insecticide use is still required.[2,3] In desert vegetable production systems, growers have been delivering high-quality, safe produce to the fresh market for decades, and this has been accomplished almost exclusively through the use of insecticides. Pest management in desert lettuce crops is chemically intensive by design and focused around the timely application of selective insecticides, not with the intent to conserve natural enemies, but to mitigate economic and dietary risks. In fact, western lettuce growers and consultants have reported that chemical control is the only effective IPM tactic available for the control of most major insect pests.[4] Naturally occurring biotic control agents are simply not capable of providing the level of crop protection necessary for meeting the marketing demands for fresh produce. In practical terms, IPM weighted towards integrating biological control is not considered feasible in conventionally grown lettuce crops in the desert southwest.

Fresh-market vegetable production in the desert growing areas of southern California and Arizona is a billion dollar industry,[5] and this region annually produces greater than 95% of the leafy vegetables (head, leaf, romaine lettuces and other specialty salad greens) consumed in the USA during the fall and winter months. These are intensively managed cropping systems that require high production inputs, such as irrigation and fertilizers, and produce a multitude of vegetable and agronomic crops year round.[6] This crop diversity, coupled with a favorable climate, provides an ideal habitat for a large complex of highly mobile and polyphagous insect pests that readily attack leafy vegetables throughout the growing season.[7] Because of the short time these crops are in the field, minor feeding activity may render the product unmarketable because of high cosmetic standards. Furthermore, lettuce crops have a high unit value, and the loss of even a small portion of the crop could be costly. Vegetable growers in the southwestern USA have concluded over time that natural enemies simply do not react quickly enough to prevent economic damage. Additionally, fresh-market grading standards do not allow for contaminants in fresh produce; thus, any insect (pest, predatory or transient species) found on the marketable crop at harvest is not tolerated. Although a number of parasitoids and predators can effectively suppress certain key insect pests of lettuce,[8] their presence on crops at harvest poses an unacceptable risk to the grower. Consequently, produce growers strive to produce a visually perfect product for the consumer, and ultimately they are forced to accomplish this chemically, and without concern for impact on biological control.

3 COSMETIC STANDARDS, CONSUMER DEMANDS AND ZERO TOLERANCE

In the production of fresh produce crops, quality is considered paramount. The grower's bottom line is to deliver a crop to the market that meets specific criteria of hygienic and visual acceptability. USDA grading standards provide the produce industry with a uniform language for describing the quality and condition of commodities in the marketplace.[9] For example, in leaf lettuce, USDA grading standards consider a 15-plant carton defective when 6% of the plants have four or more live or dead insects present (or one live or dead worm), or excreta exceeds an area 1/4 by 1 inch, or four or more holes are present. Defined tolerances further allow only minimal defects that would materially 'detract from the appearance, edibility or marketing quality of the harvested plant'. Lettuce found to exceed these tolerances may not be marketable, or may be graded lower and discounted in price. Although these USDA grading standards were originally developed to ensure consistent quality, cosmetic standards set by the food industry in the fresh market today are considered more stringent.

The current high-quality standards for produce are often presumed to be a reflection of the American consumer's demand for visual and nutritional perfection in the food they purchase. Prior to the introduction of synthetic organic insecticides, lettuce growers struggled to control insects, and particularly lepidopterous larvae. Once synthetic organic insecticides became available, they were able consistently to deliver high-quality produce, much to the delight of the finicky food-buying public, who then expected fresh lettuce always to be free of insects and damage.[10] Since then, consumers in the USA have not only come to demand blemish-free produce in the grocery store, but have shown a reluctance to purchase produce that has cosmetic defects or insect damage.[11]

More recently, the fresh produce industry has experienced significant growth in the value-added market, where lettuce and other leafy greens are prepared and sold as fresh-cut lettuce packs and ready-to-eat, bagged salad mixes.[12] The growth of this industry has also resulted in higher cosmetic standards for leafy vegetable crops, often to the point where virtually no insect contaminants or feeding blemishes are tolerated.[13] It is presumed that these changes are largely a safeguard against consumer dissatisfaction, as a grower/shipper's brand or label is clearly present on the value-added product and the consumer can readily identify the quality of the product, or the lack thereof, with the grower/shipper. Because growers cannot always dictate whether a lettuce crop from a particular field is destined to be marketed as value added or as a fresh-market product, they are forced to maintain the highest level of quality possible in all of their fields under production. Thus, by consistently producing a higher-quality product, the grower/shipper can satisfy market demands and differentiate their produce from competitors in the marketplace.

There are other market forces that influence the necessity to grow high-quality produce. From a grower's perspective, perfection is contractually demanded by the food industry, which can refuse to accept blemished produce or contaminated products.[14] Produce dealers and large retail distributors set high cosmetic standards because their contracts with growers enable their buyers visually to inspect produce before they accept it, and reject it when the supply is excessive. The bottom line is that cleaner lettuce can receive a higher price. Growers are therefore motivated to produce cosmetically perfect produce because it ensures its sale. Although these standards certainly improve the chances for a consistent supply of high-quality produce, they can also serve as a means of manipulating market supply and prices.

The practical outcome of these marketing standards for pest management is that growers of fresh-market lettuce and value-added products often act under a zero-tolerance threshold, i.e. no damage or contamination whatsoever, which inevitably leads them to use the most effective management approach – in this case, aggressive insecticide use. Most growers recognize that the cost of insecticides is low relative to the high value of the crop or, worse yet, the risk of having product rejected at the market. A recent analysis of western lettuce and insecticide usage by the CropLife Foundation, Washington, DC, suggested that economic production would not be possible without insecticides, and estimated that every dollar spent on insecticides would yield a net return of $20 in crop value back to the farm. Operating under these circumstances, growers can hardly be held accountable for their intensive pesticide use and failure to adopt biointensive pest management.

4 THE PRODUCE PARADOX

Lettuce growers often find their pest control practices coming under strong criticism by societal groups that espouse a pesticide-free food supply, or by biological control proponents who question their heavy reliance on chemical control. Yet the consumer still expects fresh produce that is of good visual quality, nutritious, safe and available year round at a reasonable price.[15] Meeting these expectations obviously presents a tremendous challenge to lettuce growers, particularly in diverse cropping systems like the desert southwest. To survive in the food industry, growers must satisfy the consumer's demand for fresh produce that is not only aesthetically appealing but also free of pesticide residues. To meet these expectations, they are encouraged to employ biointensive IPM, even though current technology is not adequate or cost effective in the desert production system. Therein lies the produce paradox – the desire for perfect produce demands pesticide-intensive IPM, but the contradictory desire of consumers, as well as a paramount goal of IPM, is to reduce pesticide use. So how do desert lettuce growers safely employ chemical control and still comply with market, regulatory and consumer demands?

5 THE ICC AND LETTUCE IPM PROGRAMS

Like most pest management programs, IPM currently used in desert vegetable crops evolved from the basic principles found in the ICC. Stern and his colleagues recognized that modern, intensive agriculture could not exist without insecticides.[1] They appreciated the complexity of agricultural cropping systems, and stressed that an understanding of biological, ecological and environmental interactions occurring within cropping systems was necessary before insecticides could be applied conservatively. In particular, they stressed the recognition of the ecosystem, development and use of population sampling and economic thresholds, and encouraged the use of selective insecticides. Discussed below are examples of how local IPM programs have integrated these concepts for controlling insects in desert lettuce to address the produce paradox.

5.1 Recognition of the ecosystem

An understanding of the cropping system, along with its influence on pest biology and ecology, allows growers to adopt or modify production practices that can be directly aimed at avoiding or preventing pest outbreaks.[10] Scientifically, this can be the most difficult set of IPM tactics to develop and research, and in practical terms the most difficult for growers to implement successfully.[16] Over the past 50 years, a great deal of information has been generated in the scientific literature on the basic biology and ecology of the key insect pests found in the desert cropping systems. Consequently, this research has contributed to pest management guidelines for cultural practices that have been employed in an attempt to prevent infestations of insect populations over time and space.[6,8]

In desert vegetable production, cultural control as an IPM tactic is inherent to crop management. Lettuce growers typically plan their crop management practices with consideration of the historical trends in pest activity as an attempt to minimize overall pest abundance in their fields and thus hopefully reduce their reliance on insecticides.[8] Examples of this include the use of optimal growing practices, which are critical for avoiding unnecessary stress on plants and should include proper management of irrigation, plant nutrition and salinity to encourage rapid emergence and growth. Crop sequencing, crop placement and timing of planting can have significant impacts on adult insect dispersal, but can also be difficult to implement in diverse cropping systems. Awareness of adjacent crops and other natural habitats is important, as crops approaching harvest (i.e. cotton and alfalfa) and weedy non-crop areas can be the primary sources of very mobile and polyphagous pest species (i.e. *Spodoptera exigua* Hübner, *Liriomyza* spp. and *Myzus persicae* Sulzer). Delaying fall planting of produce crops until after termination or harvest of cotton and alfalfa can also reduce insect migration onto seedling crops (i.e. *Bemisia tabaci* Gennadius biotype B). However, sanitation and clean culture are perhaps the most important cultural practices that can be employed by lettuce growers, particularly on an area-wide basis. Rapid post-harvest destruction of weeds and crops can reduce the magnitude and duration of insect dispersal for a number of insect species found in the surrounding crops, and it eliminates potential breeding sites. Although cultural tactics are not a substitute for chemical control in desert cropping systems, they can have an area-wide impact on some pest populations such as *B. tabaci* biotype B.[16]

5.2 Population sampling and scouting

The cornerstone of desert pest management programs is monitoring and scouting for the purpose of deciding when pesticide applications are made. This activity became so important to agricultural production that an entire profession was created in Arizona and California in the 1970s.[17] All vegetable crops in the desert are professionally scouted by licensed pest control advisors (PCAs) who must possess a university degree and maintain their credentials annually through Cooperative Extension-sponsored continuing education classes. Lettuce growers value this expertise and pay on average more than \$20.00 acre^{-1} for scouting services.[18] Furthermore, surveys suggest that PCAs intensively scout and monitor for pest abundance in 100% of the lettuce acreage grown in the desert southwest, and at least 3–4 times per week. In desert produce crops, it is also the PCA's responsibility, following scouting, to provide a written recommendation when a field requires insecticide treatment. As a consequence, the use of professional scouts in desert produce has minimized the grower's role in pest management.

Numerous sampling techniques are employed in desert produce crops to determine species identification and population abundance. Visual sampling for insects and their damage is the most reliable method, and in lettuce this generally entails the destructive examination of whole plants for insect presence and signs of feeding.[7,13,19] Other techniques, such as pheromone traps, have been used to monitor *S. exigua* and *Trichoplusia ni* Hübner in desert cropping systems, and can indicate the need for visual sampling for eggs and larvae. Yellow sticky traps have been used to identify species composition and monitor the activity of *Liriomyza* leafminers, aphids and whiteflies on head lettuce and melons in Arizona.[20,21] Unfortunately, sampling plans that recommend sample size and scouting procedures are generally nominal recommendations developed through research experience and observations.

5.3 Economic thresholds

Historically, economic thresholds and action thresholds have not been well defined for fresh-market vegetable crops. Prior to the publication of the ICC, recommendations for the use of insecticides on fresh-market vegetables crops did not typically mention spray timing. Shortly thereafter, guidelines for insecticide spray timing were subjective at best, suggesting that growers 'treat as needed' or 'repeat once or twice at weekly intervals'.[22] It has only been in the past two decades that thresholds have been incorporated into IPM recommendations for desert lettuce crops.[7,8,13] However, similar to sampling plans, most thresholds used for determining the need to treat for insect pests affecting produce crops are nominal at best.

The development and availability of action thresholds have certainly contributed to the reduction in insecticide use on desert produce crops. PCAs quickly realized that meeting market demands did not require season-long plant protection from insects, and they could delay spray applications until they were absolutely needed (i.e. near harvest). In head lettuce, for example, Toscano *et al*.[23] found it unnecessary to keep plants free from lepidopterous larvae during the entire growing season for a grower to obtain high yields and quality lettuce. Similar studies for aphid control in lettuce showed that, with proper spray timing and choice of insecticide, application numbers could be significantly reduced with no impact on marketable quality (Palumbo JC, unpublished data). Although standards set by produce retailers force PCAs to operate under a zero-tolerance environment, nominal thresholds play a significant role in keeping desert produce clean and residue free because their use can help the PCA decide when *not* to treat. This is clearly evident from surveys of insecticide use patterns where PCAs discriminate from making spray applications even though insect pests are present in the field.[18]

5.4 Selective insecticides

One of the congressionally mandated objectives of Cooperative Extension IPM programs receiving federal funding in the USA has been to reduce pesticide usage and the associated environmental and occupational risks in vegetable crops.[2] Similarly, the goal of IPM programs for lettuce and other leafy vegetables in the desert southwest has been to deliver new technologies for managing pests that reduce grower reliance on high-risk, broadly toxic pesticides without sacrificing yield, quality and profitability. Ironically, it has been the recent development of novel selective insecticides, promoted by industry as being 'compatible with natural enemies and biological control', that has had the greatest impact on pest management and insecticide use in fresh produce crops grown in the desert southwest.

Historically, vegetable growers produced unblemished and insect-free lettuce and leafy greens for the fresh market by making scheduled, routine applications of broadly toxic organochlorine, organophospahate, carbamate or pyrethroid insecticides throughout the growing season. These chemicals were cheap, effective and easy to use. In the 1970s it was not uncommon for desert growers to treat with insecticides 2–3 times a week to control lepidopterous larvae on lettuce.[10] Excessive and often indiscriminate usage eventually led to a heightened awareness of potential environmental problems and dietary risks. Shortly thereafter, public outcries for reduced pesticide use and tighter regulatory constraints resulted in fewer available insecticide options.[2] The agrochemical industry responded to these concerns by developing and registering reduced- and low-risk insecticides, most of which were selectively efficacious against specific groups of insect species.[24] Because these compounds possess very safe toxicological attributes through novel mechanisms of toxicity and routes of activity, they are considered environmentally and consumer friendly. The passage of the Food Quality Protection Act in 1996 further expedited the development and registration of reduced-risk chemistries, while slowly eliminating the availability of a number of organophosphate active ingredients.

As a result, lettuce growers in the desert are currently utilizing a suite of selective, reduced-risk chemicals to meet both market and regulatory demands. This transition has been consistent with the goals of desert lettuce IPM programs to reduce grower reliance on the older insecticides, as well as mitigate the environmental hazards associated with chemical control in the past. Table 1 shows estimates of insecticide usage on head lettuce grown in Arizona in 1996, and again from 2005 through 2009. Estimates for 1996 were generated from data collected by the United States Department of Agriculture – National Agricultural Statistical Service (NASS) surveys and show the heavy reliance by desert lettuce growers on the broadly toxic pyrethroid, organophosphate and carbamate insecticides compared with the few selective products available at that time.[25] Estimates of insecticide usage for 2005 through 2009 were generated directly from local Arizona PCAs and growers at the end of each growing season in University-of-Arizona-sponsored pest management workshops.[18] These data suggest that overall usage of the broadly toxic chemistries on head lettuce has declined steadily over the past 5 years, but, more importantly, since 1996 the usage of organophosphates and carbamates on desert head lettuce alone has declined significantly. In contrast, the use of the selective insecticides on lettuce has increased almost twofold over this same 14 year period. Results from the 2009 University of Arizona pest management workshop estimated that, for the first time, these broadly toxic compounds were actually applied to fewer acres of desert head lettuce than the selective insecticides (Palumbo JC, unpublished data).

6 ACCOMMODATING MARKET/CONSUMER EXPECTATIONS WITH SELECTIVE INSECTICIDES

The intensive insect pressure that PCAs often face in desert cropping systems elicits the question as to how these selective, reduced-risk compounds and IPM-conscious approaches can still accommodate market expectations in a zero-tolerance environment. First and foremost, most of the reduced-risk insecticides currently used are highly effective against target insect species relative to older chemistries. In head lettuce, for instance, reduced-risk active ingredients such as spinetoram, methoxyfenozide, indoxacarb, chlorantraniliprole and flubendiamide all provide quick knockdown mortality and long residual control of *S. exigua, T. ni* and other lepidopterous species in the field compared with the old industry standards, methomyl and pyrethroids.[26,27] This level of effective control alone can reduce the number of spray applications necessary to control larvae in produce crops throughout the season. Interestingly, because of the excellent control these new compounds provide, coupled with their low ecological and mammalian toxicities, use of *Bacillus thuringiensis* Berliner has essentially been eliminated in lettuce (Table 1).

Table 1. Estimated usage of broadly toxic (organophospahtes, carbamates, cylodienes and pyrethroids) and selective (reduced- and low-risk) insecticide chemistries on head lettuce in Arizona, based on NASS and PCA surveys[18,25]

Insecticides	Estimated number of head lettuce acres treated *(total acres in production)*					
	1996 *(55 000)*	2005 *(50 000)*	2006 *(48 000)*	2007 *(45 500)*	2008 *(46 000)*	2009 *(46 000)*
Broadly toxic chemistries						
Pyrethroids	256 960	182 030	169 894	148 376	150 739	147 726
Methomyl	207 900	45 150	48 114	30 986	22 523	16 555
Thiodicarb	23 595	0	0	0	0	0
Endosulfan	36 630	17 760	17 566	20 020	16 480	8 118
Acephate	27 720	9 433	6 376	11 386	14 128	9 396
Diazinon	10 285	15 800	21 758	9 646	12 150	5 075
Dimethoate	56 760	14 656	8 050	3 829	3 487	0
Total usage	*619 850*	*284 829*	*271 758*	*224 243*	*219 507*	*186 870*
Selective chemistries						
Bacillus thuringiensis	74 250	1 125	288	0	0	0
Abamectin	11 495	0	0	0	0	0
Imidacloprid	11 550	36 443	40 488	22 818	29 973	19 890
Emamectin benzoate	–	4 483	11 928	16 124	10 670	6 989
Methoxyfenozide	–	32 728	33 926	28 494	27 141	16 740
Spinosad/spinoteram	–	114 438	103 144	82 257	98 382	85 590
Indoxacarb	–	6 363	10 609	8 395	9 994	2 475
Pymetrozine	–	7 508	3 755	1 081	432	0
Acetamiprid	–	–	10 654	19 963	9 118	1 238
Spiromesifen	–	–	1 272	1 145	2 800	585
Flonicamid	–	–	–	10 385	17 738	3 420
Spirotetramat	–	–	–	–	–	33 953
Chlorantraniliprole	–	–	–	–	–	16 509
Flubendiamide	–	–	–	–	–	4 500
Total usage	*97 295*	*203 088*	*216 064*	*190 662*	*206 248*	*191 889*

Another good example has been the use of the neonicotinoid chemistries; particularly imidacloprid, which has low environmental risk and is considered an OP replacement by the United States Environmental Protection Agency (USEPA).[28] Long residual control of *B. tabaci* biotype B and *M. persicae* in lettuce can be achieved by a single, at-planting soil application.[29,30] Growers have observed that this soil use pattern can often eliminate the need for additional foliar sprays in lettuce. This preventive management approach has been the industry standard since imidacloprid was first registered in 1993, and has been applied on as much as 80% of the head and leaf lettuce acreage planted annually in the Arizona and California deserts.[31]

Prior to registration of imidacloprid, produce growers had 3–4 chemical classes, with different modes of action, available to manage both insects and insecticide resistance. Today, PCAs working in produce crops have an additional ten chemistries at their disposal, each with a unique mode of action, and not all of them traditional neurotoxins (Table 2). Many of the modes of action for these new chemistries exploit alternative nerve receptor sites, novel physiological processes and other key biochemical functions specific to insects.[32] This has not only made them safer for the user and consumer, but in many cases more efficacious than the neurotoxins used in the past. Improved efficacy may largely be a result of their inherent insect toxicity, but issues with insect resistance to the older organophosphate and pyrethroid chemistries have played a role as well.[28,33,34]

Perhaps one of the most practical attributes associated with some of these new chemistries is their route of activity, which provides flexibility in how they are applied and can make them more effective, and in some cases safer to use. Many of the newer reduced-risk compounds have translaminar activity, which allows them topically to penetrate leaf tissues and form a reservoir of active ingredient within the leaf (Table 2). This provides quick knockdown and residual activity against certain foliar-feeding insects that typically feed within or on the underside of leaves (i.e. *T. ni*, *Liriomyza* spp. and *B. tabaci* biotype B). Because the active ingredient can move translaminarly through plant tissues, contact spray coverage is less critical for pests that can be difficult to reach with foliar sprays. This often results in more precise spray timing, where growers can effectively utilize aerial or low-volume applications when control is critically needed, rather than preemptive or delayed applications with ground equipment when access to fields is not possible owing to irrigation.

Another practical attribute associated with many of the newer chemistries is their systemic properties. As a result of their physiochemical characteristics, the neonicotinoids and diamides have excellent systemic properties that allow them to be applied in diverse ways such as soil drenches, chemigation, in-furrow and subsurface soil applications and seed treatments.[28] From a safety standpoint, when these compounds are applied to the soil during planting operations or through drip chemigation, there is minimal exposure to applicators and farm labor. This selective use of a toxicologically selective insecticide is also environmentally sound in desert cropping systems. Similarly, the newly registered diamide compound chlorantraniliprole has demonstrated systemic control of lepidopterous larvae and *Liriomyza* leafminers in lettuce when

Table 2. New selective insecticide chemistries with unique modes of action presently registered for use on desert lettuce crops, their EPA toxicological profile and effective spectrum of insect control

Selective chemistry	Active ingredient	Mode of action	Route of activity[a]	Toxico-logical profile[b]	Effective insect spectrum on desert lettuce crops[c]					
					LEP	APH	WF	FB	LM	WFT
Neonicotinoid	Imidacloprid	Nicotinic	T, SS	OPR		**X**	**X**	**X**		
	Acetamprid	Acetylcholine receptor antagonists	T	RR		X	X	X		
	Thiamethoxam		T,SS	RR		X	X	X		
	Dinotefuron		T,SS	RR		X	X	X		
Spinsoyns		Nicotinic								
	Spinosad	Acetylcholine receptor agonists (allosteric)	T	RR	**X**				**X**	**X**
	Spinetoram		T	RR	X				X	X
Mectins	Emamectin	Chloride channel activators	T	OPR	**X**					
	Benzoate									
JH analogs	Pyriproxyfen	Juvenile	T	RR			**X**			
		Hormone mimics								
Selective feeding blockers	Pymetrozine	Unknown or nonspecific	T	RR		**X**				
	Flonicamid		T	OPR		**X**				
Thiadiazinanone	Buprofezin	Chitin synthesis inhibitors, type 1	V	RR			**X**			
Diacylhydrazines	Methoxyfenozide	Ecdysone agonists	In	RR	**X**					
Indeno-oxadiazines	Indoxacarb	Sodium channel blockers	In	RR	**X**					
Ketoenols	Spiromesifen	Lipid synthesis inhibitor	T				X			
				RR						
	Spirotetramat			FS		X	X			
Diamides	Flubendiamide	Ryanodine receptor modulator	T		X					
				RR						
	Chlorantraniliprole		T,SS		X				X	

[a] Route of activity: SS, soil systemic; T, translaminar; V, vapor/inhalation; In, ingestion but not translaminar; FS, foliar systemic.
[b] Toxicological profile based on USEPA registration: RR, reduced-risk; OPR, organophosphate replacement.
[c] **X** denotes that the active ingredients are commercially efficacious against the insect: LEP, lepidopterous larvae; APH, aphids; WF, *Bemisia* whiteflies; FB, flea beetles; LM, *Liriomyza* leafminers; WFT, *Frankliniella occidentalis.*

applied exclusively to the soil as an in-furrow application or through drip irrigation.[35] This compound offers real potential savings to the grower and the environment, where recent field studies in lettuce suggest that as many as three foliar applications necessary for *S. exigua* and *T. ni* control during stand establishment can be eliminated with a single at-planting soil application of chlorantraniliprole (Palumbo JC, unpublished data). Another systemic insecticide, spirotetramat (ketoenol), was recently registered for use on desert produce crops. Although it has no practical soil activity, following foliar application and uptake, the insecticide is translocated acropetally and basipetally within the entire vascular system.[36] Research to date has shown excellent residual activity against aphid species such as *Nasonovia ribisnigri* Mosely and *Aulacorthum solani* Kaltenbach in lettuce that typically require repeated applications for economic control.[37] Again owing to its foliar systemic activity, spray coverage with spirotetramat is not as critical as with many older, conventional compounds.

Overall, the use of newer, selective compounds over the past decade in desert produce crops has certainly reduced the risk of exposure to toxic insecticide residues for consumers and farm workers. One indication of their safety is the fact that the preharvest interval (PHI) and re-entry interval (REI) for most of the reduced-risk products are short (1–3 days for PHI; 4–12 h for REI) owing to their low mammalian toxicities. In contrast, most intervals for organophosphates labelled for use in produce are quite long (PHI = 10–21 days; REI = 24–72 h). Perhaps the most telling sign has been the overall reduction in the number of foliar spray applications made to desert lettuce crops over the years. Anecdotal estimates made by older PCAs from the desert southwest suggest that, in the 1980s, an average of 12–15 sprays were applied to lettuce annually. USDA statistics estimate that, in 1996, growers applied an average of nine foliar insecticide applications to lettuce.[25] Most recently, PCA surveys in Arizona estimated that a range of 4–7 foliar sprays were applied to lettuce crops in 2007.[18] Although these trends suggest that environmental and dietary risks have been greatly reduced for desert vegetable crops with local IPM programs, ironically, produce growers still face challenges from the threats of insecticide resistance, secondary pest outbreaks, high insecticide costs and regulatory constraints that Stern and colleagues warned against about 50 years ago.

7 PRESENT CONSTRAINTS AND FUTURE CHALLENGES

Although chemically intensive pest management in desert produce remains firmly entrenched primarily owing to market forces, the changeover of IPM to safer and more effective insecticides from highly toxic, broad-spectrum insecticides of previous decades has been a welcome development. In addition to the positive attributes already described, many of the newer compounds are used at greatly reduced rates in lettuce and leafy vegetables that result in lower pesticide loads in the environment. However, because of a number of mitigating factors, the transition to reduced-risk and OP-replacement insecticides has not been as complete as it might have been.

7.1 Economics of IPM

One important challenge currently facing growers is the relative increase in the expense associated with IPM in desert produce. Perhaps most evident are the costs of newer, selective insecticides relative to conventional compounds that have been off patent for many years. As a compound matures and loses its patent protection, other companies can gain access to the active ingredient and formulate their own proprietary products. With multiple companies formulating or selling generic versions of an insecticide, pricing competition intensifies and typically drives the cost lower. Thus, higher-priced new compounds must compete with cheaper, older compounds that are often still highly effective against a target pest. As many growers desire to utilize the new, safer insecticide technology, their insect control costs have increased. Annual survey data have estimated that the average amount growers spent to control insects on head lettuce was \$30.90 acre^{-1} in 2005, but, owing to rising costs for the newer compounds and application expenses, this climbed to over \$44.00 acre^{-1} in 2009. As mentioned previously, scouting fees that PCAs charge growers for their services are now above \$20 acre^{-1}, whereas in 2002 these same fees were less than \$15 acre^{-1}. Finally, increases in fixed and variable production costs for produce have recently placed pressure on PCAs to control insects more cheaply. As growers strive to maximize profit margins, using the less expensive, older chemistries remains an attractive option.

7.2 Selectivity versus broad-spectrum activity

A second factor that may delay adoption of more selective new chemistry and IPM-conscious approaches is that PCAs are often more familiar with older products and feel more confident using them against pest populations that are still susceptible. Some of the newer modes of action may act only against specific life stages and involve a considerable lag time before the impact on the target population is visible.[38] In contrast, there is a satisfaction for growers that comes with immediate knockdown of an infestation when quick-acting older insecticides are used. Similarly, PCAs often feel compelled to apply more broadly toxic insecticides in combination with the newer selective active ingredients to achieve broad-spectrum control of multiple pest species occurring simultaneously on a lettuce crop. They often consider that the addition of the broad-spectrum insecticide provides insurance against secondary pests and helps to avoid follow-up treatments for the larger pest complex beyond the primary target. Unlike the secondary pest outbreaks that occurred after the usage of the organochlorine insecticides described by Stern *et al.*,[1] the narrow spectrum of arthropod pests controlled by a single application of the newer, selectively efficacious insecticides can also result in secondary pest outbreaks. There are often numerous secondary pests that have been traditionally held in check by an insecticide treatment targeted at a different primary pest species (analogous to the actions of natural enemies). Recent years have seen the rise of certain species that were rarely a problem before transition to selective insecticides.

A recent example of this in desert produce involves the western flower thrips, *Frankliniella occidentalis* Pergande, on lettuce crops. The first occurrence of *F. occidentalis* on desert lettuce was reported in 1958 in Yuma, Arizona.[39] Although this thrips species was known to be an occasional pest of seedling cotton, it was not considered an economic pest of lettuce.[40] Furthermore, early pest management guidelines for desert lettuce crops make no reference to thrips management,[8] and it was not until a decade ago that pest management guidelines for *F. occidentalis* were first published for lettuce.[6] It is likely not coincidental that *F. occidentalis* attained economic status soon after the introduction and widespread usage of selective insecticides on lettuce, beginning in 1993 with imidacloprid, and in 1997 with spinosad, tebufenozide and pymetrozine. The registration of these new compounds reduced the grower's need to treat lettuce with organophosphates, carbamates, pyrethroids and endosulfan for several foliage-feeding and sucking pests. Based on damage estimates and insecticide control requirements, *F. occidentalis* is now considered one of the most economically important pests found in desert lettuce.[18]

7.3 Training and education

In contrast to the general comfort that most PCAs feel with conventional insecticides, there remains some tentativeness with respect to newer insecticides that are often slower acting (i.e. insect growth regulators). The timing of applications is also usually much more critical if only a specific stage is vulnerable to the treatment.[38] Without specific guidance provided through extension services or from the manufacturer, many pest managers may feel content just to stick with the status quo. The issue of proper guidance available to those in the field charged with carrying out pest management is serious and worthy of examination beyond this article.

At a time when the need for training and education of personnel carrying out chemically intensive IPM programs is arguably greater than ever owing to the dramatic increase in novel modes of action, the land-grant universities, as the responsible educational institutions of the agricultural sciences, are reducing personnel devoted to these disciplines. The Cooperative Extension Service in US land-grant universities has traditionally been the source of new agricultural information available to the agricultural community as needed. However, state and federal funding for extension has been in decline for several years, and little evidence suggests a reversal of the trend.[17] With cuts in resources and personnel in the agricultural sciences, many universities are no longer available to deal adequately with pressing, on-farm issues. Ultimately, what this means is that the expertise may not be available to train and educate PCAs on the complexities of these novel compounds, or assist in their implementation in existing IPM programs. Rather than receiving the necessary guidance to move over to a more selective insecticide regime that favors natural enemies, the potentially uncertain PCA may just opt to continue on with what is familiar.

As the availability of this traditionally objective, research-based information diminishes, the crop protection industry and commodity groups may play a larger role in providing advice on when and how to integrate new insecticide technologies into vegetable production systems. Internationally, this problem of gaining expertise in the use of selective new insecticides may be more severe, as the infrastructure for pest management education and training is often lacking. A recurring criticism of IPM has been that it is oriented more for the scientist than for the practitioner, and that wider adoption of IPM is precluded owing to its technical nature.[41,42] The failure to educate sufficient numbers of people in agricultural sciences and train them in the specifics of IPM represents a serious constraint to the adoption of progressive IPM practices in developed and underdeveloped countries alike.

7.4 Consumer perceptions

The failure of education extends well beyond the field to public perceptions of agriculture and the manner in which food is grown and insect pests controlled. In the USA there is an almost complete disconnection between the polished produce found in supermarkets and where it comes from, as well as how it is produced. The transition from agrarian to post-industrial societies has resulted in lifestyles that have been streamlined in terms of the way food is presented and consumed. Today's consumers have come to expect increased levels of convenience and choice in the produce they purchase. Produce items that were once considered seasonal are available year round, and consumers now expect the convenience of opening up a bag of salad that is already prepared and ready to serve. Along the way, a few key events have occurred that survive as cultural impressions, including DDT, the poisoning of food and the killing of birds and butterflies that no longer sing or brighten the springtime.[43] While this is no doubt a gross oversimplification, it does speak to similar oversimplifications that occur in the social consciousness regarding the production of food. It is the very attitude that is addressed by the produce paradox. This is obviously an issue that transcends multiple facets of human life in the twenty-first century, but ultimately has repercussions for the manner in which IPM is conducted now and in the future.

7.5 Insecticide resistance

One of the key risks associated with the produce paradox and other behavioral influences on the way IPM is conducted is the problem of insecticide resistance. In spite of the proliferation of new insecticide technologies, development of resistance among specific insect pests continues to be a concern.[44] The desire for perfect produce, the simple convenience and low cost of applying an insecticide compared with a non-chemical solution to a pest infestation and the unfortunate failure to adopt an insecticide use strategy that takes into account fundamental resistance management techniques all contribute to the phenomenon of insecticide resistance. At the local level, the lack of a resistance management strategy may stem from ignorance of differences among modes of action that result in two or more treatments per crop season from the same insecticide family. At the regional level, a failure to coordinate insecticide use strategies among neighboring growers or among various crops can lead to multiple exposures of a pest population to one or more modes of action.[45] At the level of the insecticide manufacturer, there is a failure among individual companies conservatively to market their products in order to avoid multiple exposures among consecutive generations of a pest population to one or more modes of action. Needless to say, this problem is even more pronounced when agrochemical companies allow market dynamics to determine which product gets used when and where, apparently without any consideration to restraining market saturation in order to prevent overlapping use of one or more modes of action. Paradoxically, cases of severe insecticide resistance have often been the catalysts for transitioning to newer, less familiar insecticides as a last resort. The collective faith in the idea that a new product will always be on the other side of a crisis seems to have been instilled by historical examples.[46] While the threats about waning pesticide discovery have been preached over a period of decades, chemical manufacturers, remarkably, have continued to deliver new and effective insecticides. And desert lettuce growers have come to expect them. A tremendous expansion in new modes of action provides pest managers with an amazing repertoire of diverse products, but aforementioned concerns regarding the absence of resistance management strategies still represent a serious threat to the long-term viability of insecticides. In addition, there are external market forces such as pesticide regulatory actions that also have the potential to influence IPM and resistance development.

7.6 Regulatory constraints

When the Food Quality Protection Act (FQPA) was implemented in 1996, agricultural economists warned that one of the consequences of the regulatory action would be a sharp reduction in the availability of many chemical tolerances for desert vegetables, and eventually higher growing costs and food prices. Thus far, the impact of FQPA on the desert produce industry has been minimal. Some restrictions have been placed on a few older compounds, including endosulfan and diazinon, and the use of dimethoate has been voluntarily removed from use in head lettuce. Although FQPA has been largely responsible for the expedited registration of many of the reduced-risk and OP replacement chemistries presently used in lettuce (Table 2), it has also indirectly affected the economics of IPM through higher insecticide costs. However, the most significant impact from FQPA may be a few years away. FQPA requires USEPA to develop and initiate a screening procedure to remove from the market pesticide active ingredients that negatively affect estrogenic or other endocrine systems in humans. The agency recently announced that it will begin initial screening of 67 pesticide active ingredients under the endocrine disruptor screening program. Among the pesticides on this list are methomyl, bifenthrin and endosulfan, three key compounds that provide broad-spectrum insect control, but perhaps more importantly play key roles in local resistance management programs for *F. occidentalis* and *B. tabaci* biotype B. It is not known how these compounds will fare during this process, but the loss of these compounds in desert lettuce crops could place tremendous selection pressures on the spinosyn, neonicotinoid and ketoenol chemistries.

Regulatory actions can also impact upon local IPM and resistance management programs on an international scale. It has been estimated that between 6 and 14% of the lettuce and other leafy vegetables grown annually in the desert southwest are destined for export markets, and in particular for Canada, Japan and Europe. These global markets provide desert lettuce growers with niche opportunities to sell fresh-market and value-added produce, but not without trade regulations that can influence pest management decisions made by the grower. Dealing with issues involving maximum residue levels (MRLs) as they apply to fresh produce destined for export markets has become increasingly frustrating for domestic growers and shippers. In a sense, trade barriers have been created between nations as the regulatory agencies in the importing countries have established MRLs at lower levels, or not at all for new compounds, as a means of regulating trade in treated food and avoiding excessive residues of older pesticides (i.e. pyrethroids). Furthermore, most of the newer insecticides, after completing rigorous registration procedures through the USEPA, are prohibited from use on crops destined for these foreign markets because MRLs have not yet been established there. This lack of harmonization in MRLs can result in substandard IPM if insecticide alternatives are limited. For example, during the 2008 growing season, desert growers producing lettuce for a large shipper were prohibited from using flonicamid, chlorantraniliprole, flubendiamid, spirotetramat and spinetoram on any of the shipper's vegetables, regardless of whether they were destined for domestic or export markets. Although less than 5% of the shipper's produce was grown for export, product destined for these markets could be harvested from random fields, depending on sales and quality. Thus, because these countries had no established MRLs for these four compounds, the shipper was not willing to risk their usage. In this particular case, the grower had adequate alternatives for insect management, but it could have had serious economic consequences if the alternative insecticides had not performed. Until global MRLs are similarly established among food-trading nations, it will be difficult to integrate safer insecticides into existing management programs.

8 CONCLUSION

The caveats in Stern *et al.*[1] regarding inherent limitations to the ICC are very much brought to mind in light of the current state of IPM for fresh-market lettuce and other leafy vegetables in desert agricultural valleys of the southwestern USA. The circumstances under which IPM is practiced extend well beyond individual growers and their personal decision-making processes. Conventional lettuce growers are obliged to conform to market standards established by produce buyers and shippers with whom they contract. The zero-tolerance standard for damage or contamination of the harvested product informally established by the marketplace is the primary constraint to adopting a more balanced IPM program. Similar situations in the marketplace for fresh produce existed 50 years ago, when Stern *et al.*[1] raised their point about constraints to integrating biological and chemical controls. Paradoxically, however, zero-tolerance standards have become more stringent even as public concerns about excessive pesticide inputs to agriculture and unsafe residues in food have increased.

Owing to the bioeconomic approaches presented in the integrated control concept, IPM offers a sufficiently robust template for addressing the public's concerns. However, there are significant policy concerns that would need to be addressed before proceeding forward. So far, the marketplace's response to such concerns has been best represented by the organic produce movement.[46] This segment has witnessed tremendous growth in the past 2–3 decades, even though it still remains a proportionally tiny part of the overall produce market. There is undoubtedly middle ground between organic lettuce and lettuce crops grown conventionally under zero-tolerance restrictions. Finding this middle ground, assuming sufficient desire exists, will be a complex process involving different sets of priorities from different segments of society. Whether the point has been reached for a serious discussion about the future of food is debatable. Ultimately, consumers will have to argue the trade-offs between cosmetic appearance and insecticide risk. And if biointensive IPM is what they agree upon, they will have to accept less than perfect produce.

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